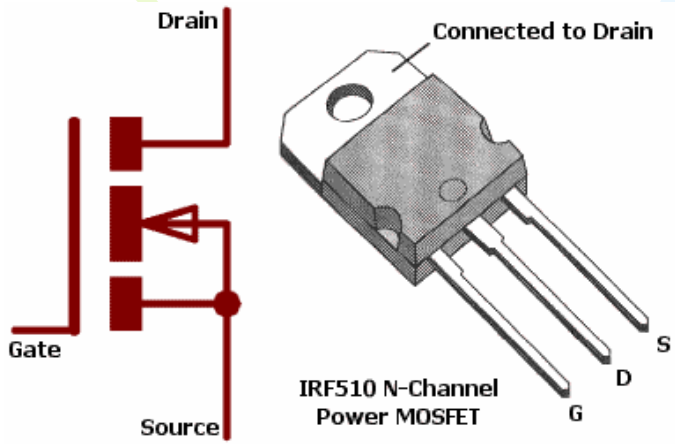
Lecture 07

Metal-Oxide-semiconductor Field-EffectTransistors (MOSFETs)



圖片來自casemods.pointofnoreturn.org/pwm/mosfets.html

topics

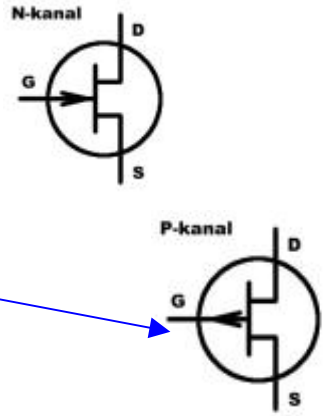
- FET’s physical operation
- MOSFET’s current-voltage characteristic

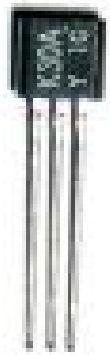
Why FET ?

- Small size (5% BJT)
- Little operation power
- Simple Manufacturing process
- Easy to implement VLSI

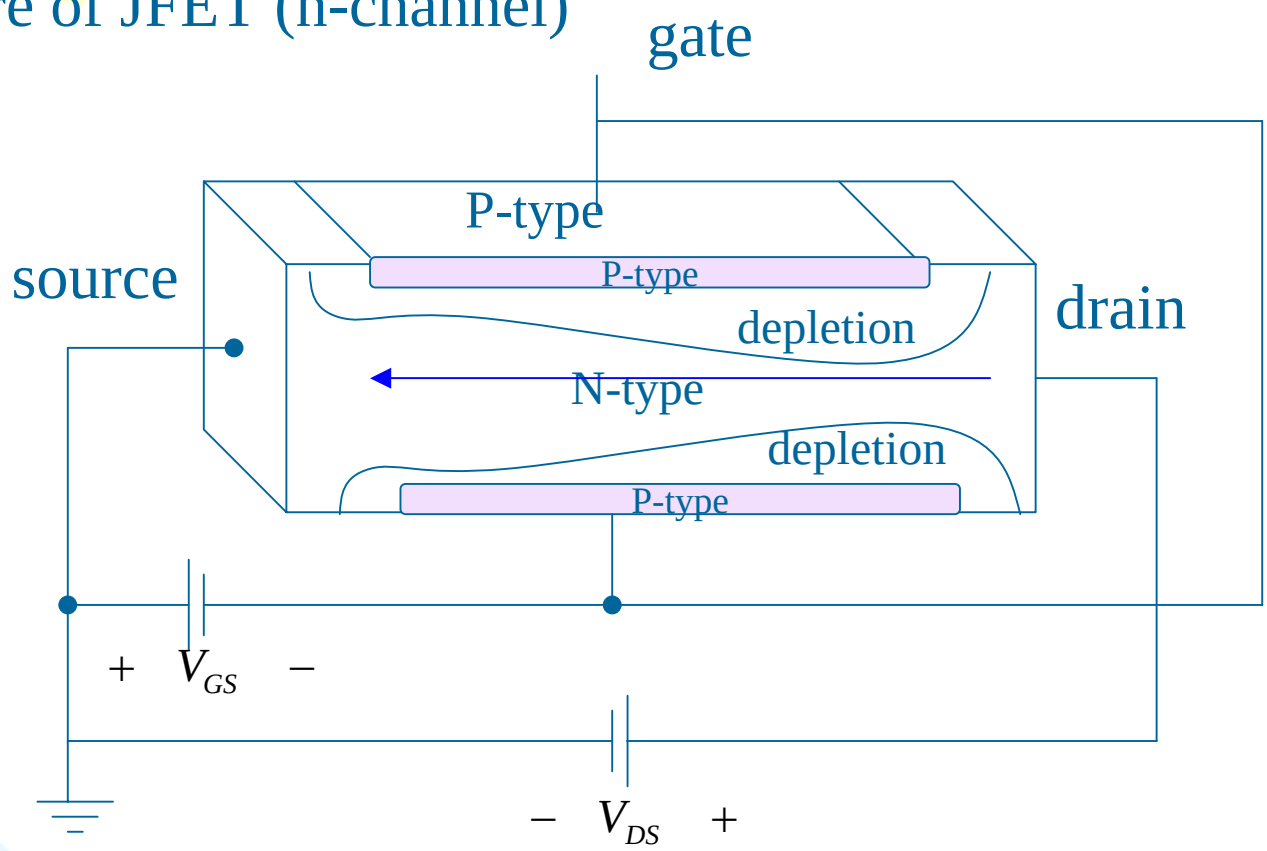
Classification

- MESFET
- JFET
  - Depletion
    - N-channel
    - P-channel
- MOSFET
  - Depletion
    - NMOS
    - PMOS
    - CMOS
  - Enhancement
    - NMOS
    - PMOS
    - CMOS





Structure of JFET (n-channel)

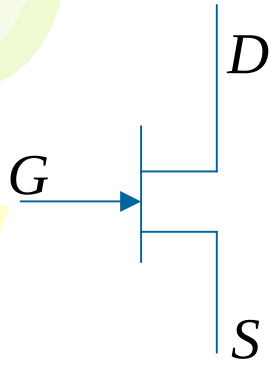


$V_{GS} = 0 \Rightarrow I \equiv I_{DSS}$

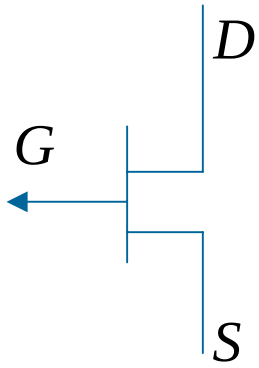
Reverse V_{GS} ↗ →depletion region ↗→channel ↘→I↘

Reverse V_{GS} ↗↗→ depletion region ↗↗→channel ~0 →I=0 (pinch off)

symbol of JFET

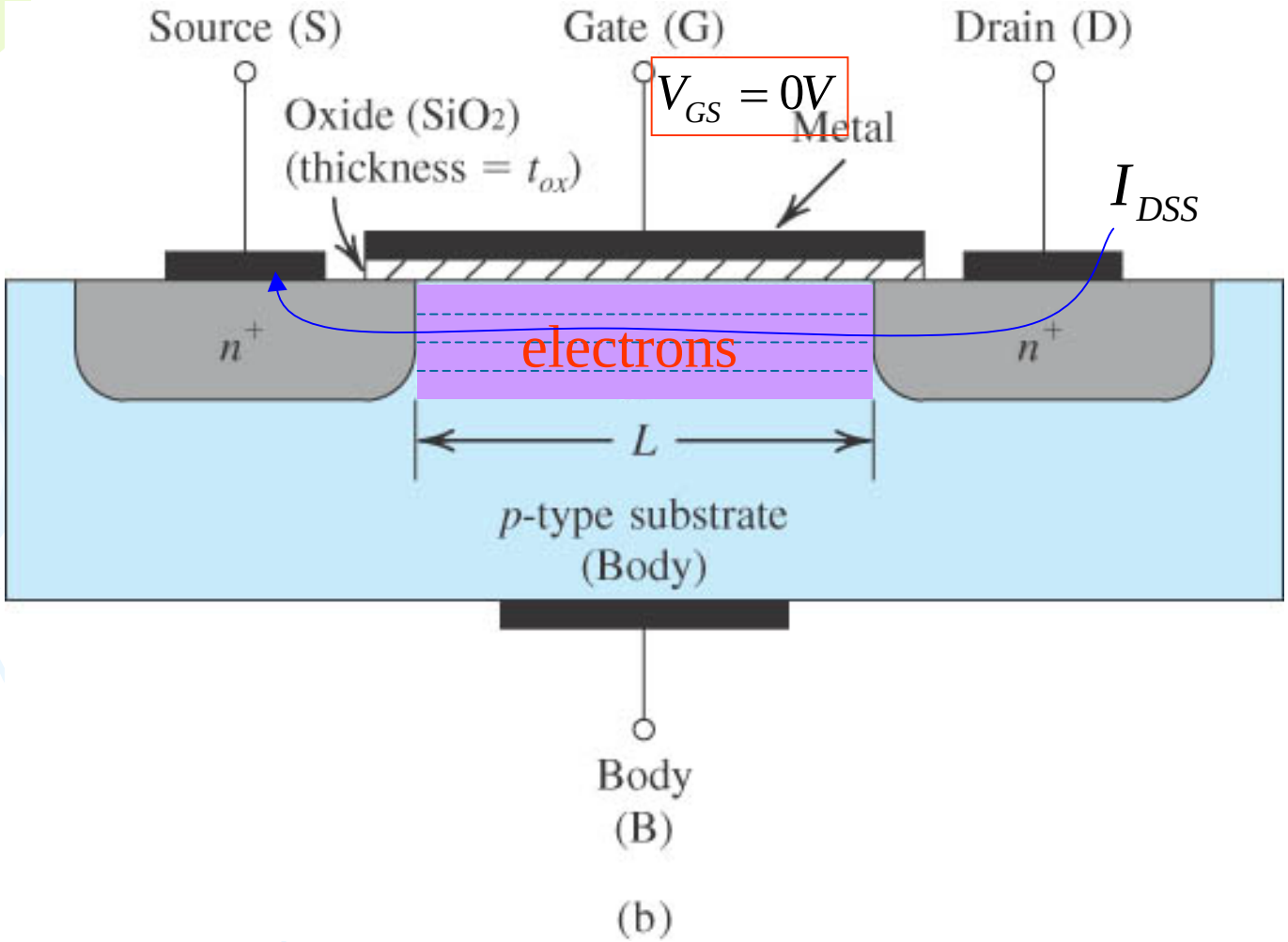


N-channel



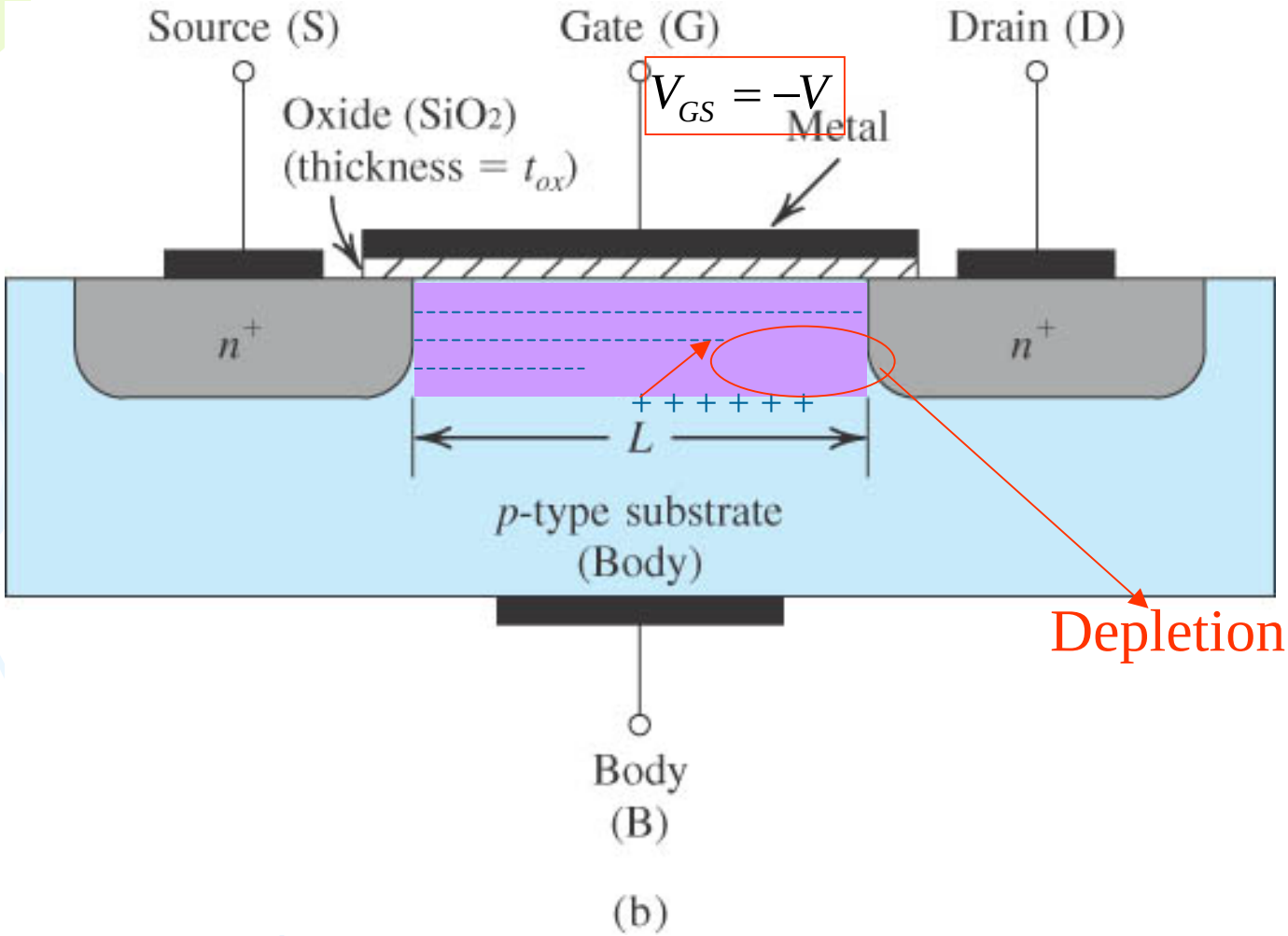
P-channel

Structure of depletion-type MOSFET (n-channel)



(b)

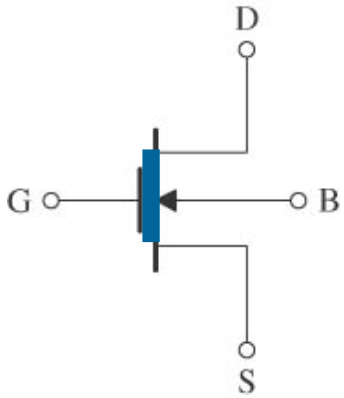
depletion-type MOSFET (n-channel)



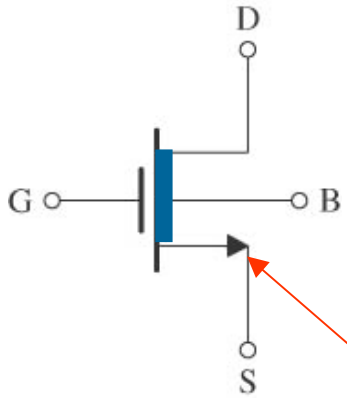
(b)

symbol of depletion-type MOSFET

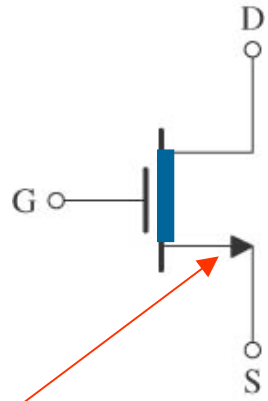
NMOS



(a)



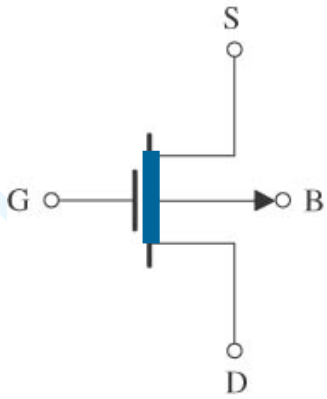
(b)



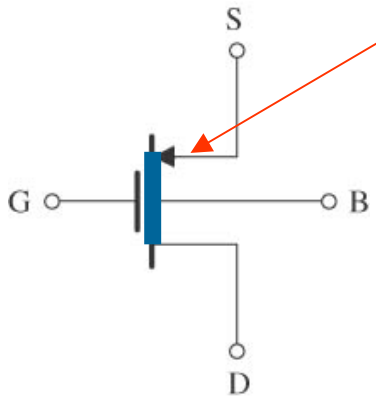
(c)

Current direction

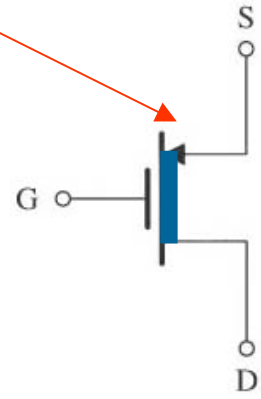
PMOS



(a)

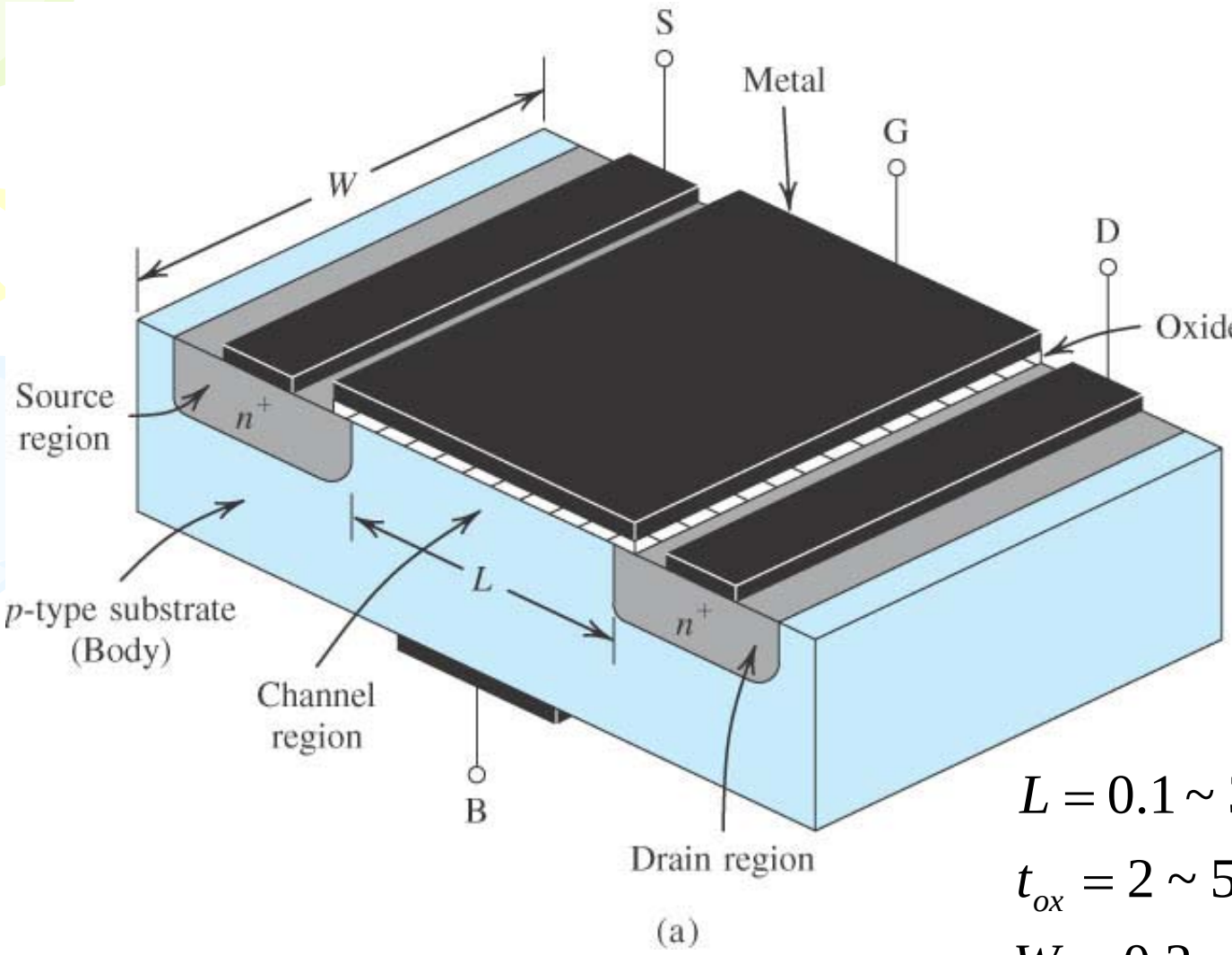


(b)



(c)

Structure of enhancement-type NMOS transistor



insulator

$10^{10} \sim 10^{15}\,\Omega$

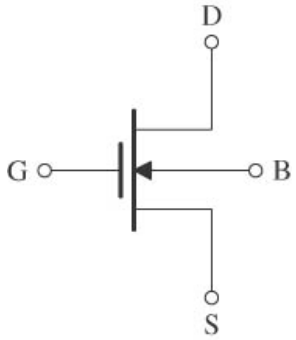
$$L = 0.1 \sim 3\mu m$$

$$t_{ox} = 2 \sim 50nm$$

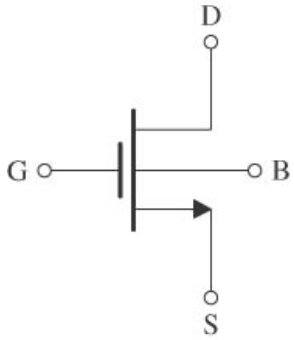
$$W = 0.2 \sim 100\mu m$$

symbol of enhancement-type MOSFET

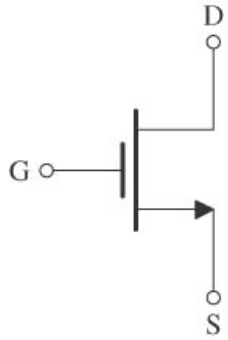
NMOS



(a)

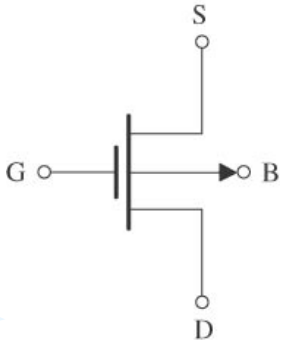


(b)

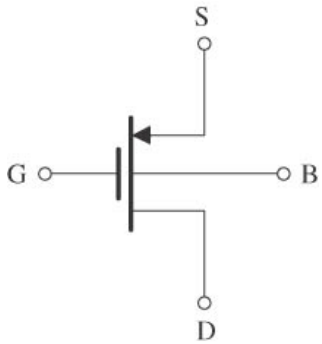


(c)

PMOS



(a)



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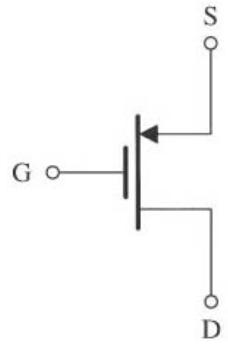

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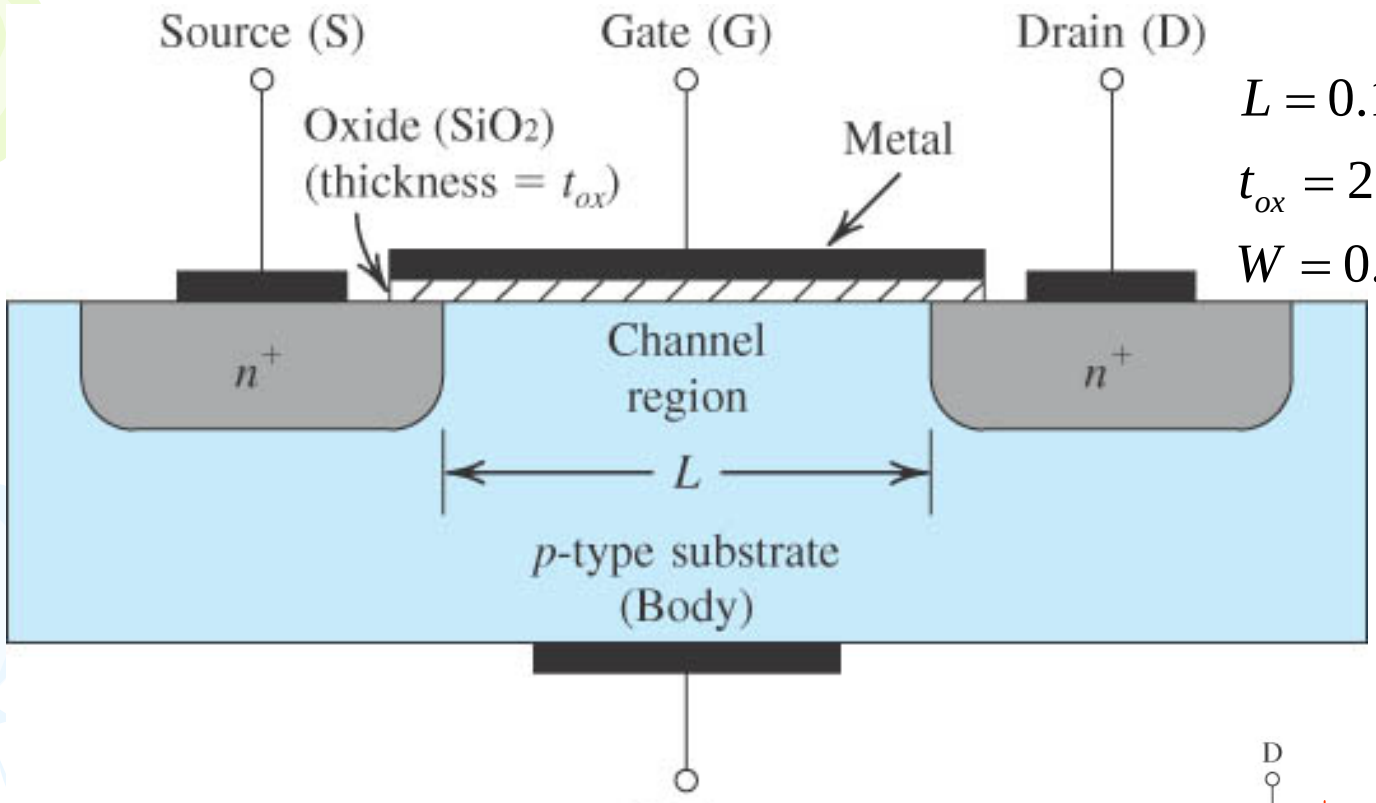
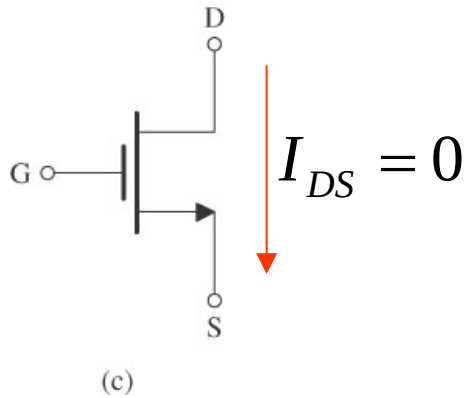


(b)

$L = 0.1 \sim 3\mu m$

$t_{ox} = 2 \sim 50nm$

$W = 0.2 \sim 100\mu m$



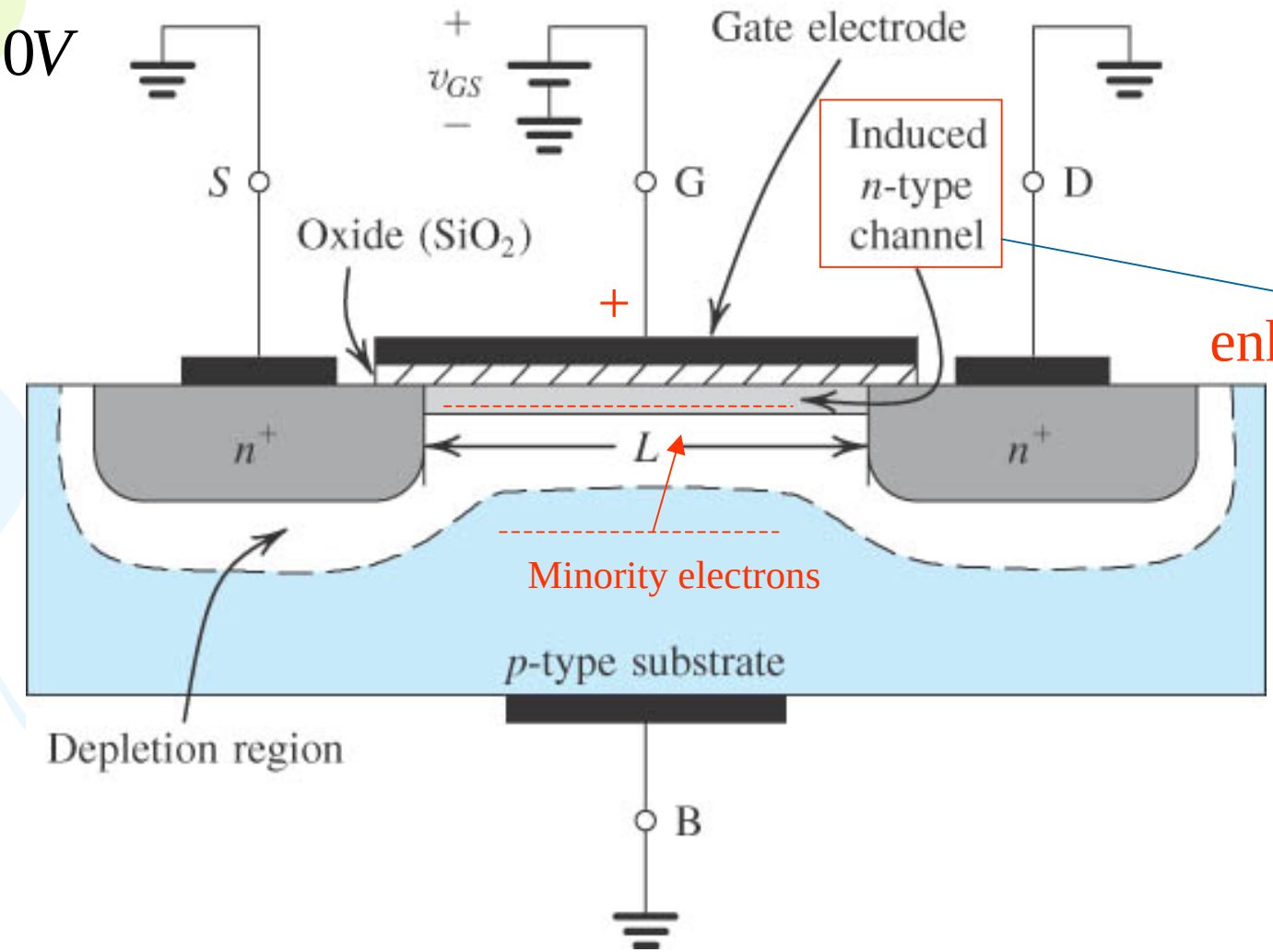
(c)

if $V_{GS} = 0, \quad (V_{GS} < V_t)$

$\rightarrow I_D = 0, R_{DS} \approx 10^{12}\Omega$

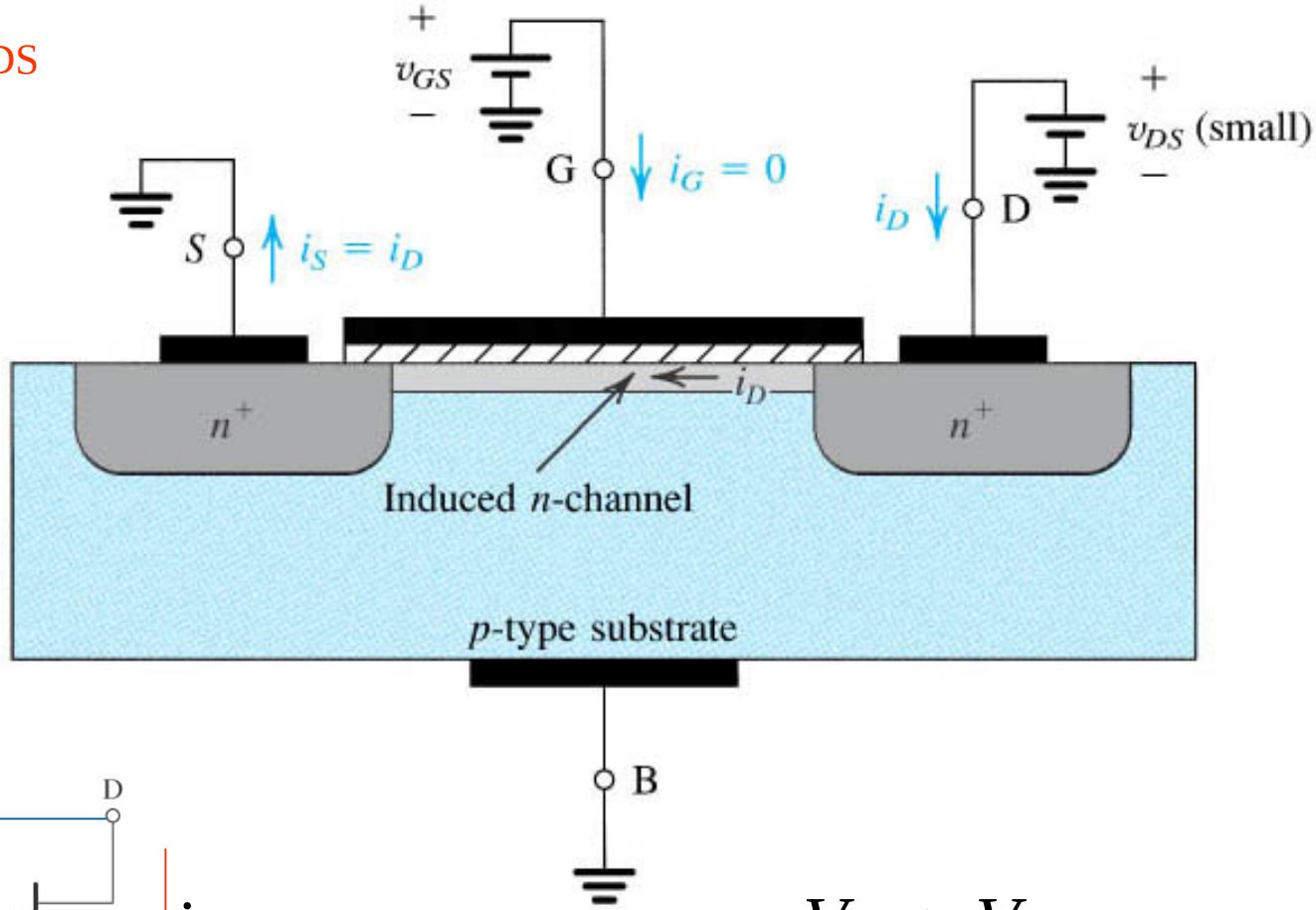
$V_{GS} > V_t$

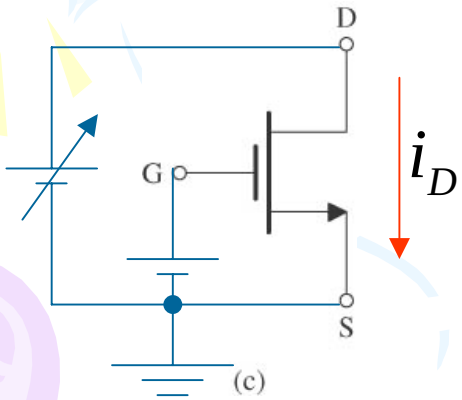
$V_{DS} = 0V$



enhancement

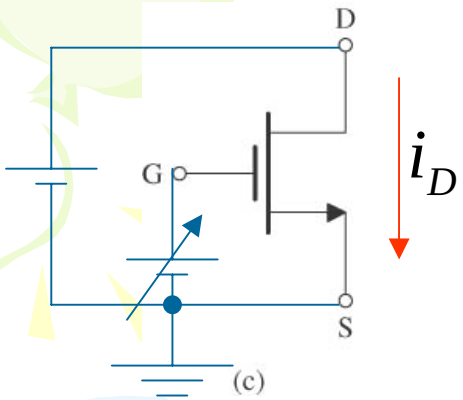
Small V_{DS}

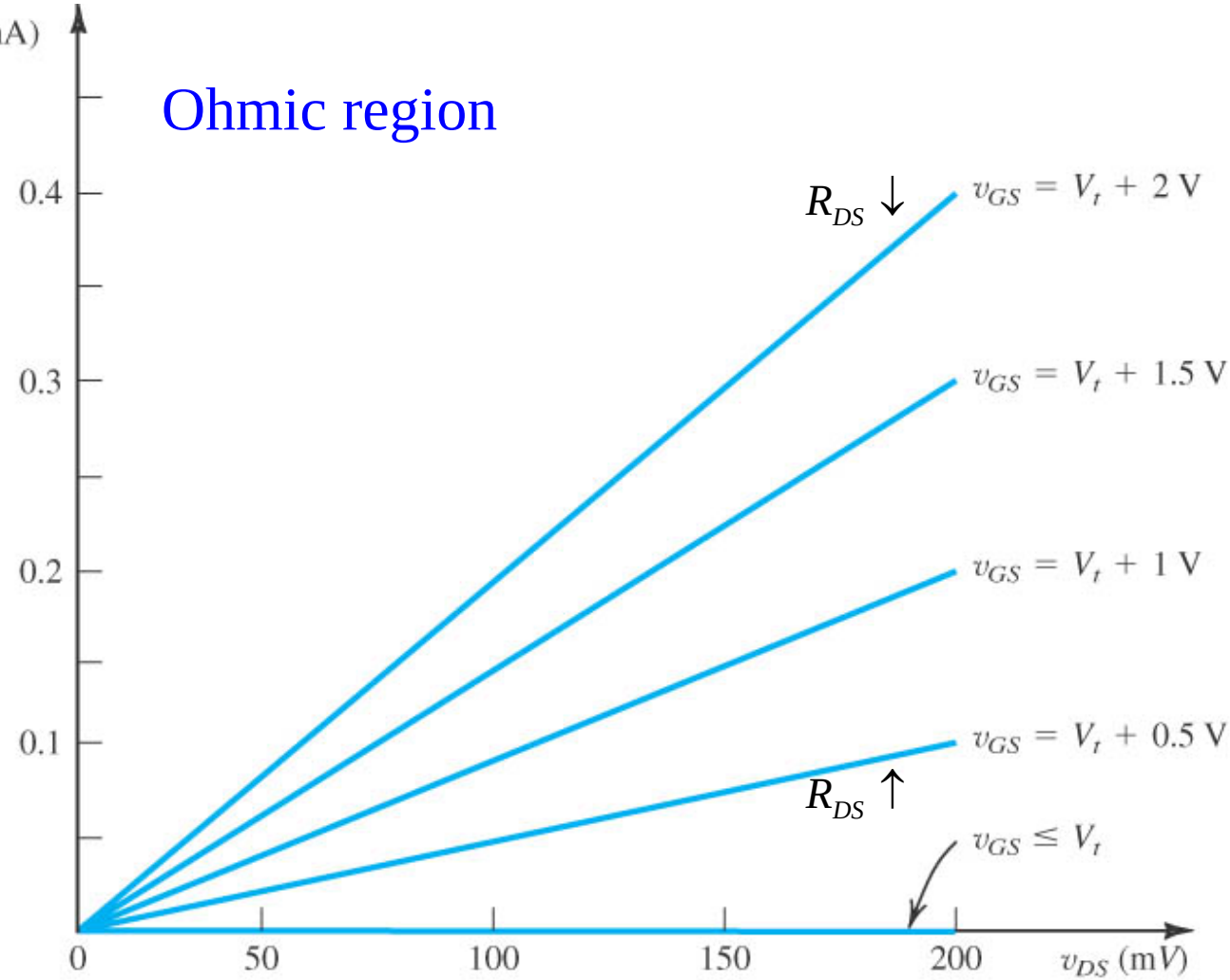




$$V_{GS} > V_t$$

$$V_{DS} \uparrow \Rightarrow I_D \uparrow$$





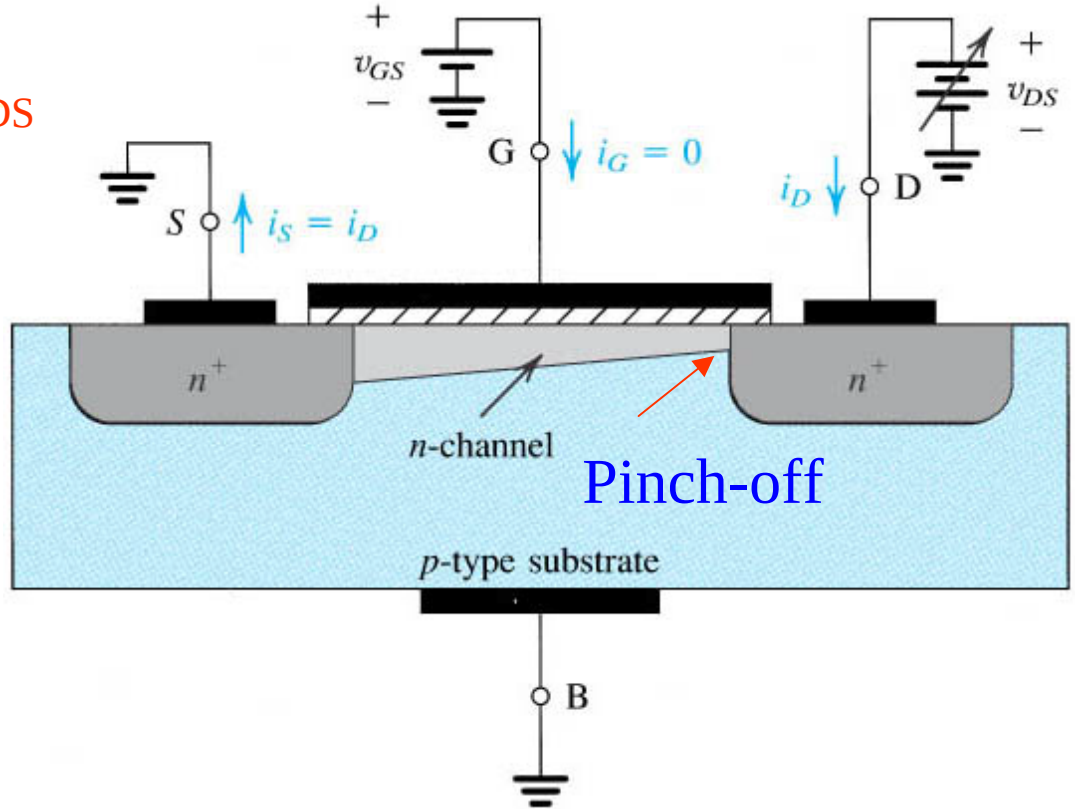
Ohmic region

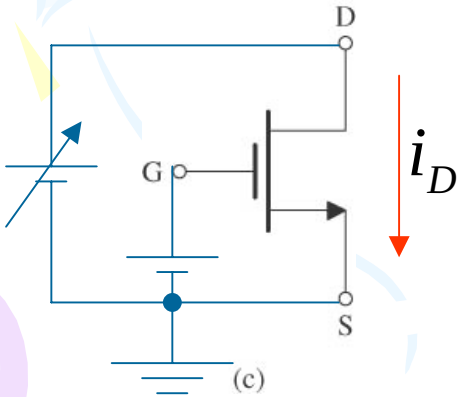
$$V_{GS} > V_t$$

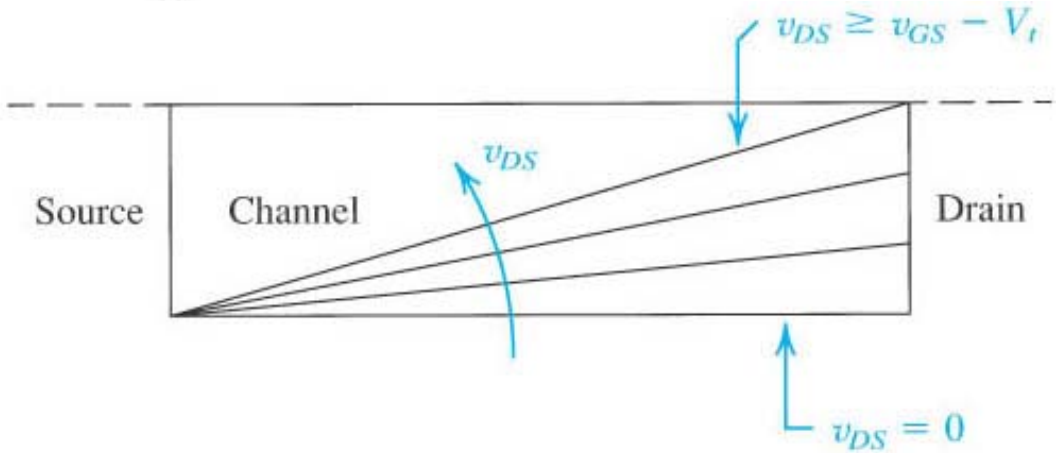
$$V_{DS} \uparrow \Rightarrow I_D \uparrow$$

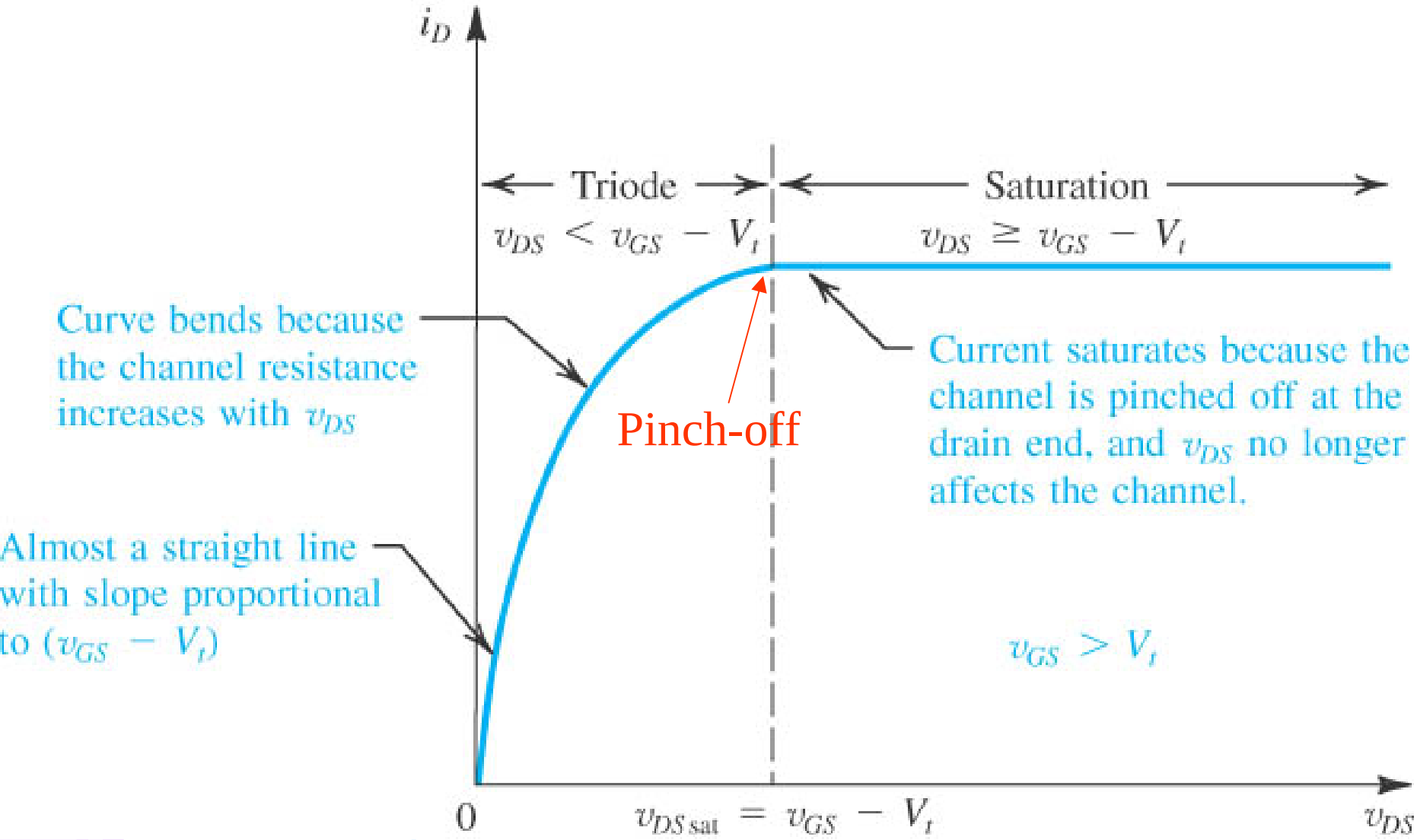
Resistance characteristic

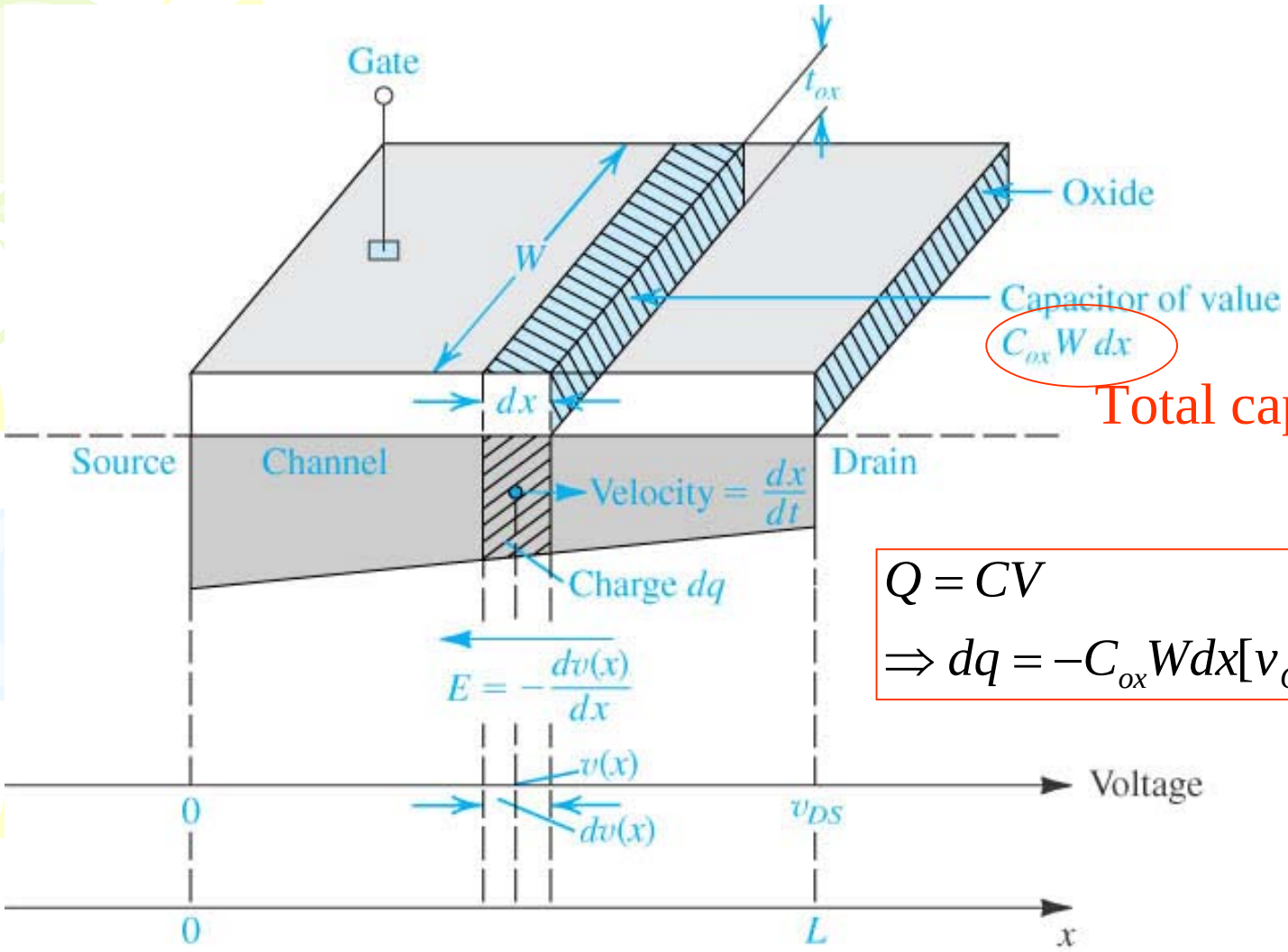
large V_{DS}


+
v_{GS}
−
G
$i_G = 0$
S
$i_S = i_D$
i_D
D
+
v_{DS}
−
n^+
n^+
n-channel
Pinch-off
p-type substrate
B


D
G
S
i_D
(c)


$v_{DS} \geq v_{GS} - V_t$
v_{DS}
Source
Channel
Drain
$v_{DS} = 0$


i_D
Triode
$v_{DS} < v_{GS} - V_t$
Saturation
$v_{DS} \geq v_{GS} - V_t$
Curve bends because the channel resistance increases with v_{DS}
Pinch-off
Current saturates because the channel is pinched off at the drain end, and v_{DS} no longer affects the channel.
Almost a straight line with slope proportional to $(v_{GS} - V_t)$
$v_{GS} > V_t$
0
$v_{DS\,sat} = v_{GS} - V_t$
v_{DS}



Total capacitance at dx

$$Q = CV$$

$$\Rightarrow dq = -C_{ox}Wdx[v_{GS} - v(x) - V_t]$$

C_{ox} : capacitance per unit gate area

$$i = \frac{dq}{dt} = \frac{dq}{dx}\frac{dx}{dt}$$

$$dq = -C_{ox}Wdx[v_{GS} - v(x) - V_t]$$

$$\frac{dx}{dt} = -\mu_n E(x) = \mu_n \frac{dv(x)}{dt}$$

$$\Rightarrow i = -\mu_n C_{ox} W[v_{GS} - v(x) - V_t]\frac{dv(x)}{dx}$$

$$i_D = -i = \mu_n C_{ox} W[v_{GS} - v(x) - V_t]\frac{dv(x)}{dx}$$

$$i_D dx = \mu_n C_{ox} W[v_{GS} - v(x) - V_t]dv(x)$$

$$\int_0^L i_D dx = \int_0^{v_{DS}} \mu_n C_{ox} W[v_{GS} - v(x) - V_t]dv(x)$$

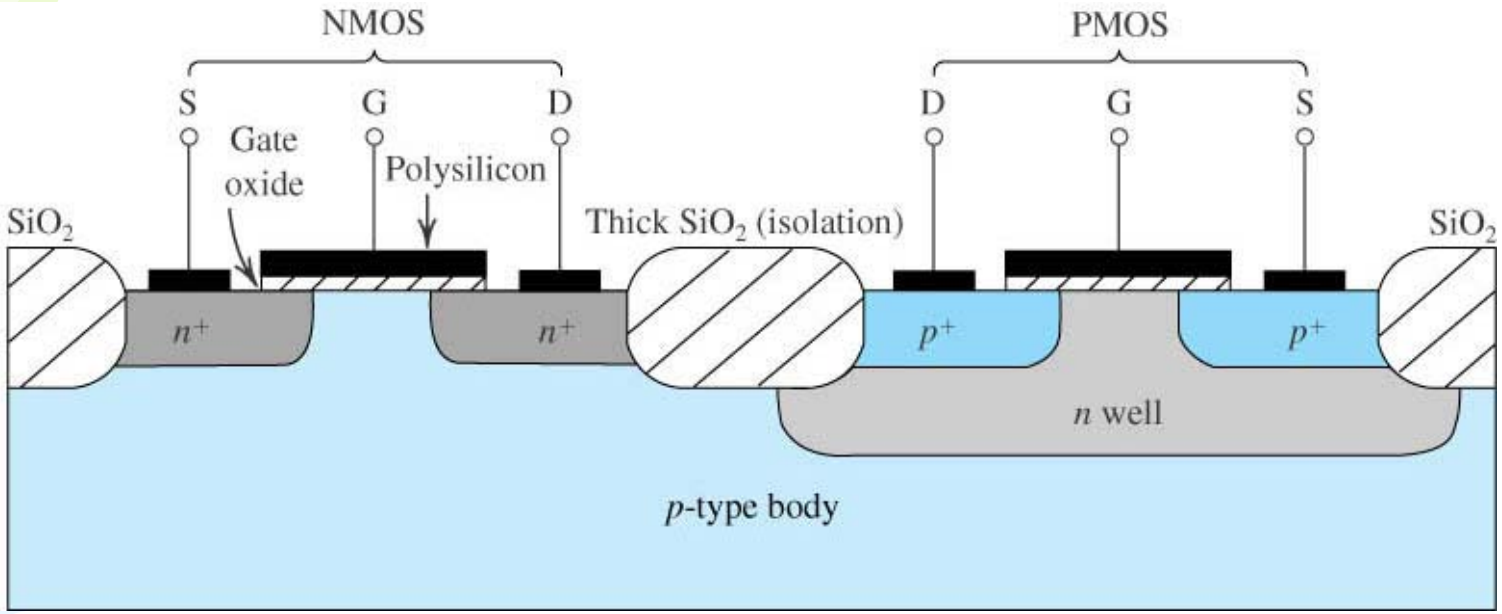
$$i_D = \mu_n C_{ox}\frac{W}{L}[(v_{GS} - V_t)v_{DS} - \frac{1}{2}v_{DS}^2]$$ Ohmic region

$$\therefore v_{DS} = v_{GS} - V_t$$ Saturation region

$$\Rightarrow i_D = \mu_n C_{ox}\frac{W}{L}[(v_{GS} - V_t)^2 - \frac{1}{2}(v_{GS} - V_t)^2]$$

$$i_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(v_{GS} - V_t)^2$$ Saturation region

Structure of enhancement-type CMOS transistor



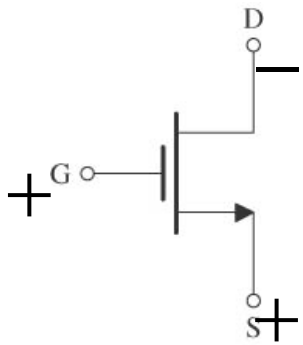
EMOSFET operation mode

- Ohmic (triode) region
- Saturation region
- Cutoff region

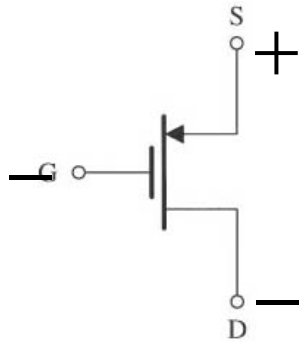
$$v_{DS} \le v_{GS} - V_t \qquad v_{SD} \le v_{SG} - |V_t|$$

$$v_{DS} \ge v_{GS} - V_t \qquad v_{SD} \ge v_{SG} - |V_t|$$

$$v_{GS} \le V_t > 0 \qquad v_{SG} \le |V_t|, \quad V_t < 0$$

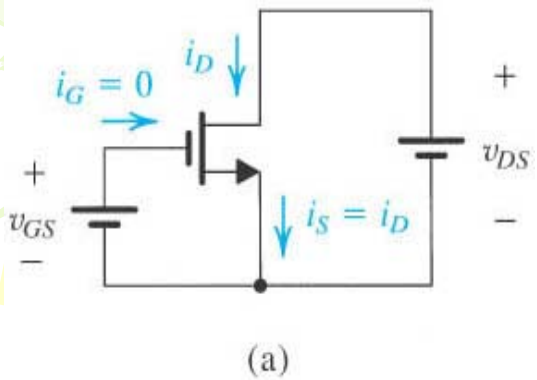


(c)

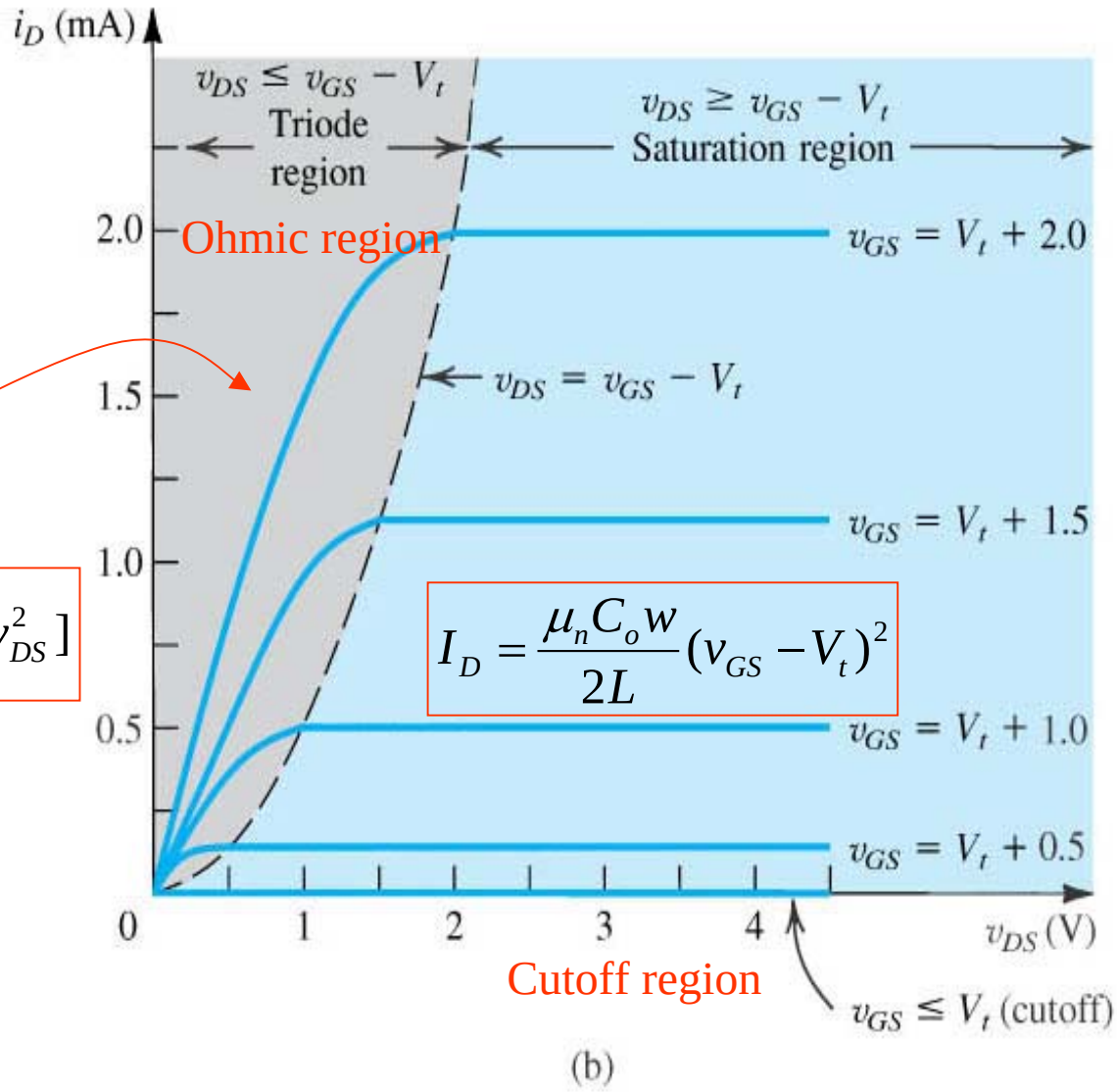


(c)

NMOSFET current-Voltage characteristic



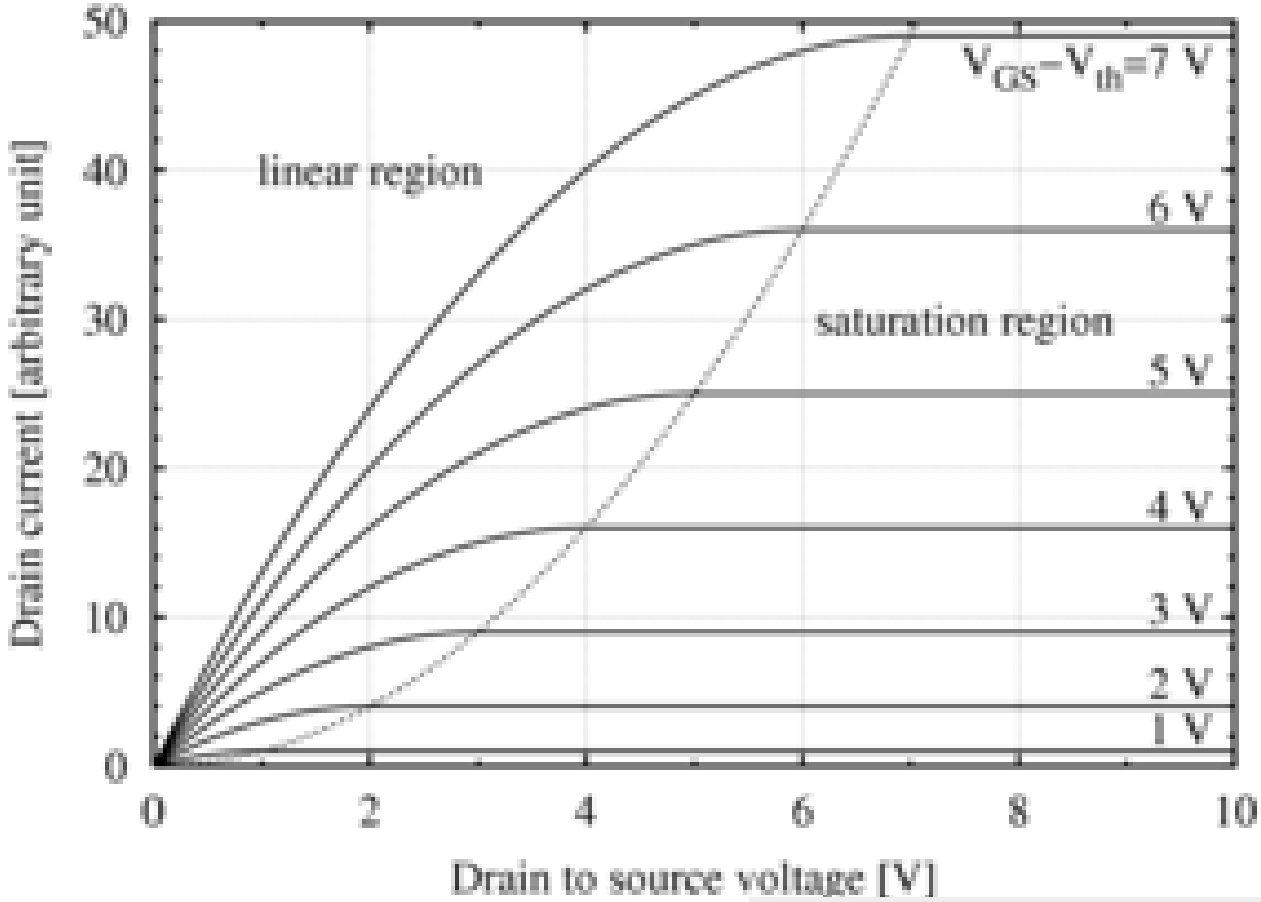
(a)



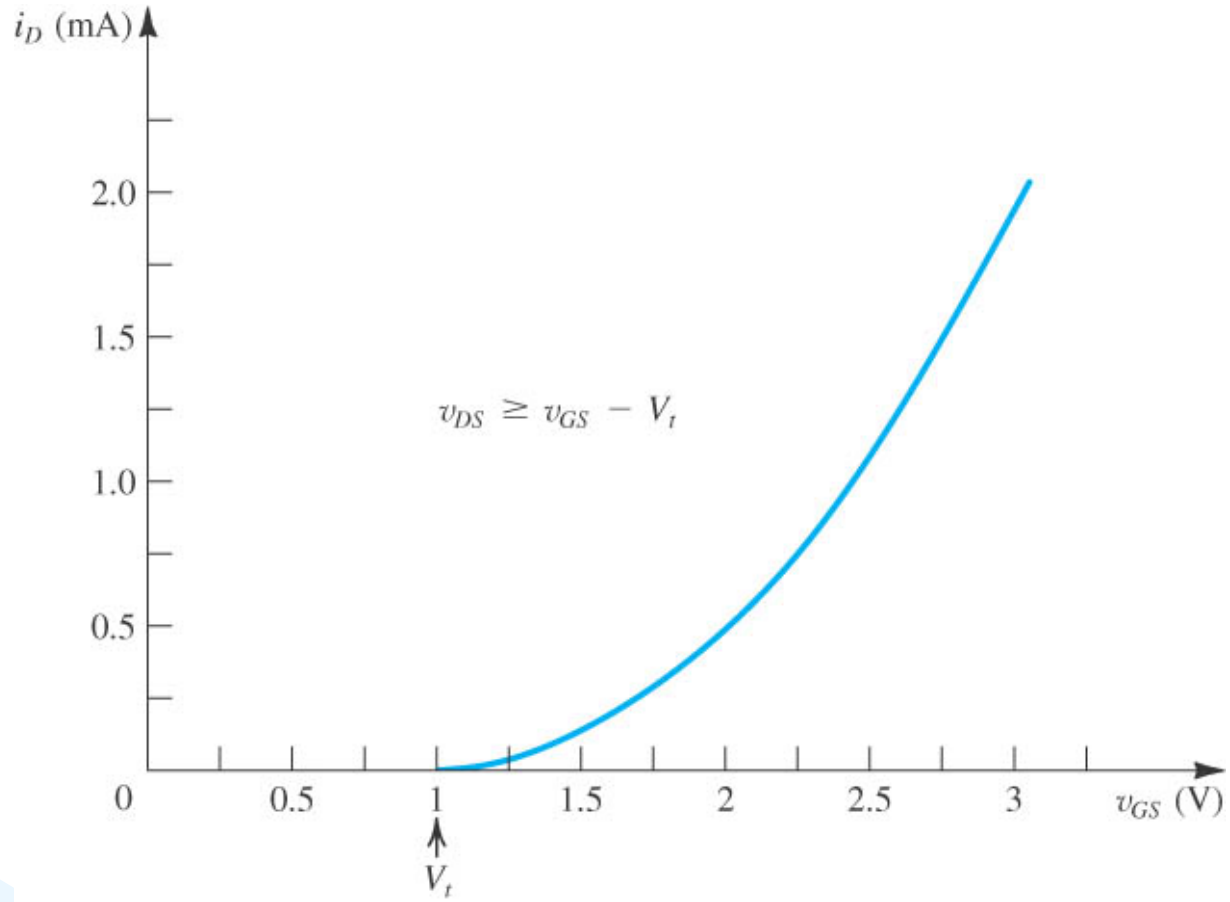
(b)

$$I_D = \frac{\mu_n C_o w}{2L}[2(v_{GS} - V_t)v_{DS} - v_{DS}^2]$$

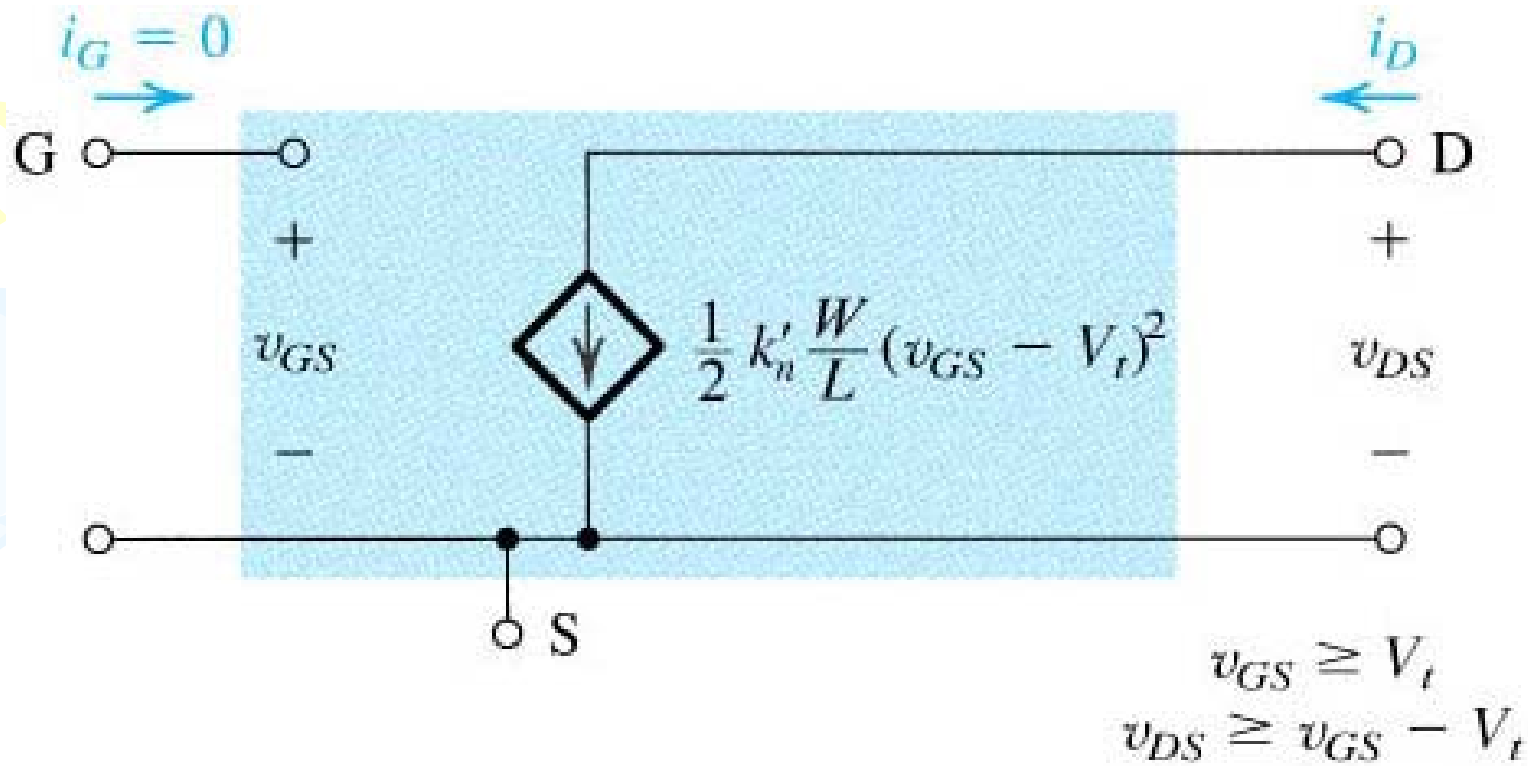
$$I_D = \frac{\mu_n C_o w}{2L}(v_{GS} - V_t)^2$$



圖片來自en.wikipedia.org/wiki/MOSFET

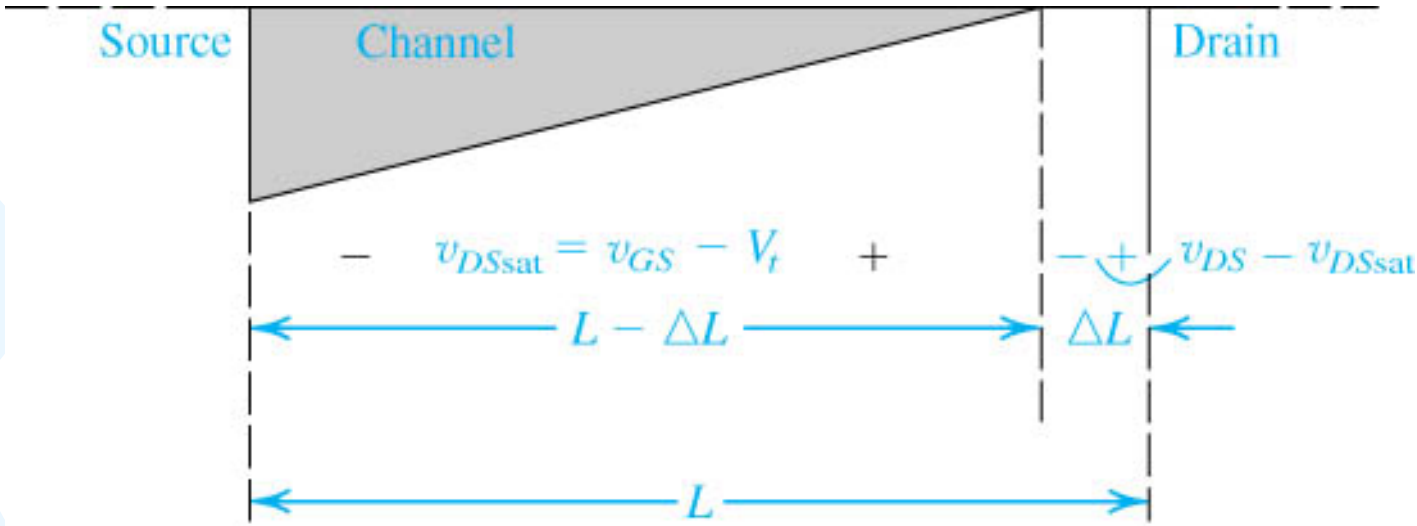

i_D (mA)
2.0
1.5
1.0
0.5
0
0.5
1
1.5
2
2.5
3
v_{GS} (V)
$v_{DS} \geq v_{GS} - V_t$
V_t

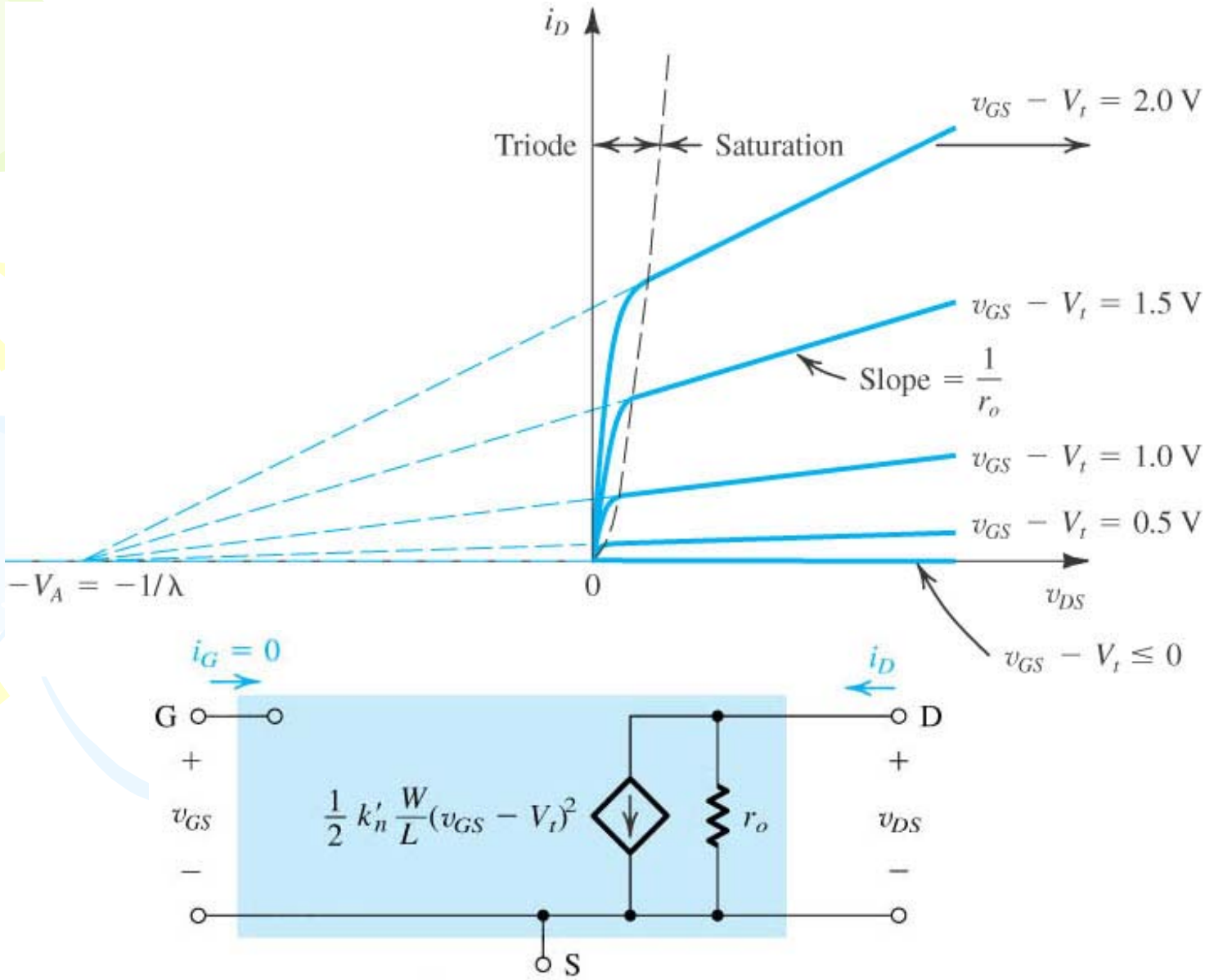
$$I_D = \frac{\mu_n C_o w}{2L}(v_{GS} - V_t)^2$$

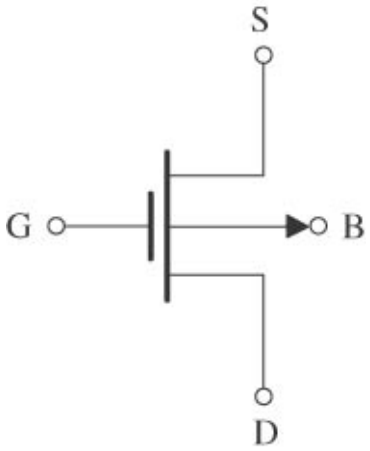


Saturation region large-signal model

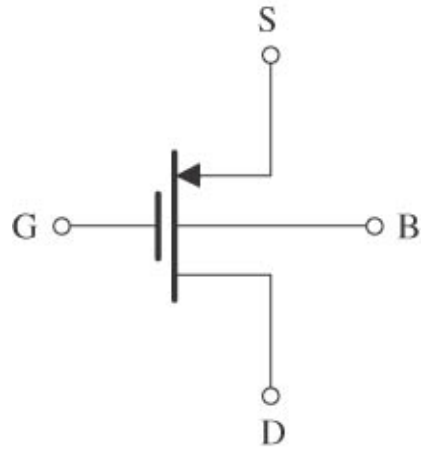
Channel length modulation (as Early effect)



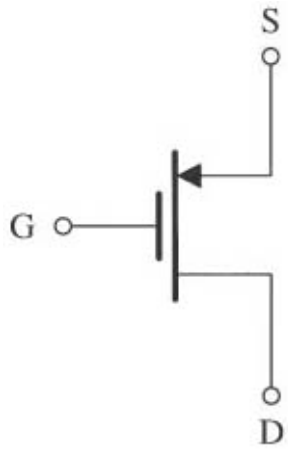

i_D
Triode
Saturation
$v_{GS} - V_t = 2.0$ V
$v_{GS} - V_t = 1.5$ V
Slope $= \frac{1}{r_o}$
$v_{GS} - V_t = 1.0$ V
$v_{GS} - V_t = 0.5$ V
$-V_A = -1/\lambda$
0
v_{DS}
$v_{GS} - V_t \leq 0$
$i_G = 0$
i_D
G
D
+
v_{GS}
−
$\frac{1}{2} k'_n \frac{W}{L}(v_{GS} - V_t)^2$
r_o
+
v_{DS}
−
S



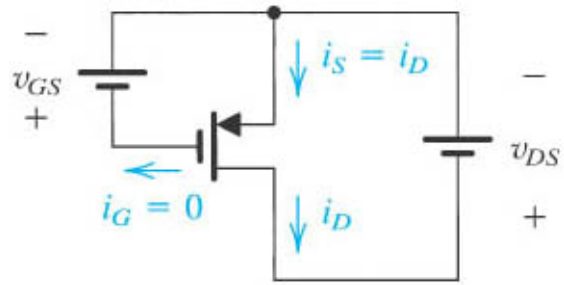
(a)



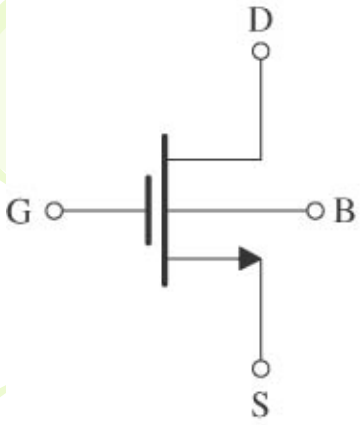
(b)

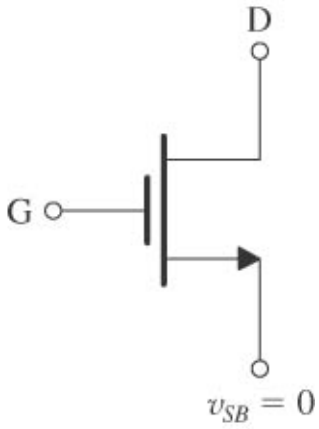


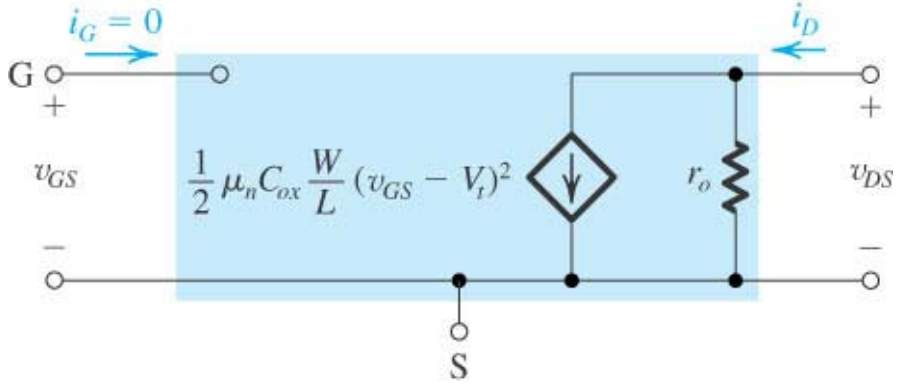
(c)

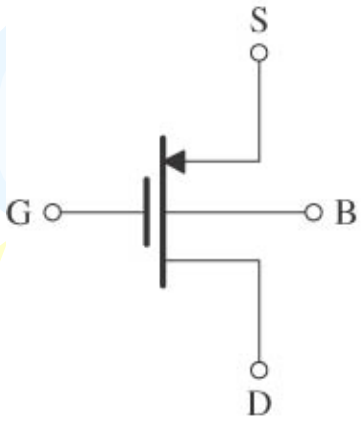


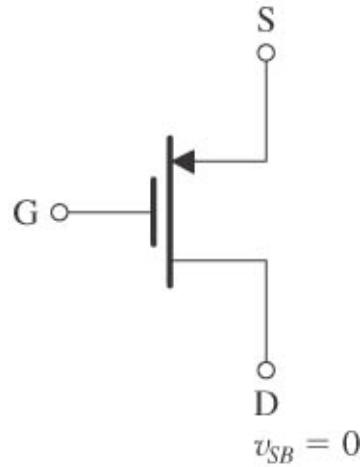
(d)

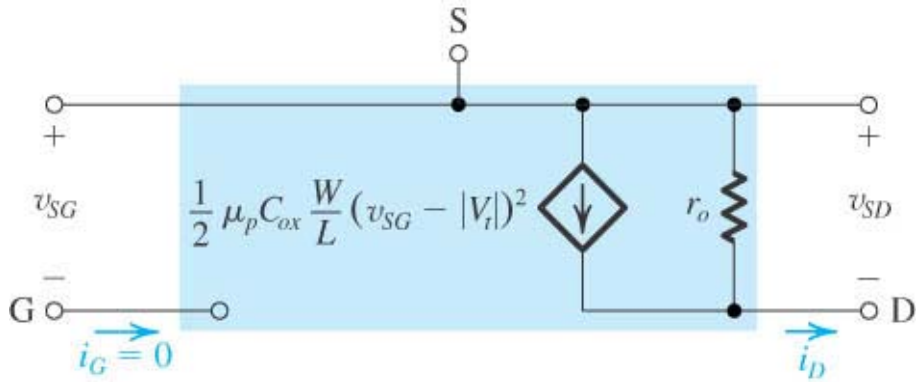

D
G
B
S


D
G
$v_{SB} = 0$


$i_G = 0$
i_D
G
+
v_{GS}
–
$\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(v_{GS} - V_t)^2$
r_o
+
v_{DS}
–
S


S
G
B
D


S
G
D
$v_{SB} = 0$


S
+
v_{SG}
–
$\frac{1}{2}\mu_p C_{ox}\frac{W}{L}(v_{SG} - |V_t|)^2$
r_o
+
v_{SD}
–
G
D
$i_G = 0$
i_D